

ON
CERTAIN LAWS OF COHESIVE ATTRACTION.

BY
JAMES D. DANA.

Read before the American Association of Geologists and Naturalists, held at
Boston, September, 1847.

FROM the account of cohesive attraction in works on Chemistry, we gather little more than what the term itself implies; and in the higher treatises on Physics, the subject is discussed on general mathematical principles, and mostly without reference to observed facts, excepting those of the most obvious character. This is especially true of the attraction in solidification. I propose to consider what observation teaches on this subject, and would ask the attention of the Association to a brief statement of a series of facts, and to certain obvious inferences from these facts.

The objects to which we appeal for illustration, are the rocks and minerals of the earth, and the ordinary forms of inorganic matter. The grand principle has already been recognized, that solidification and crystallization are the same process. As early as 1807, in the Lectures on Natural Philosophy by the learned Thomas Young,* this philosopher says, after some explanatory remarks, "It appears, therefore, consistent both with reason and experience, to suppose that a crystallization more or less perfect is the universal cause of solidity." Biot in his *Précis*† recognizes the same principle; and other names favoring this conclusion might be mentioned. The fact is obviously exemplified in nearly every inorganic solid around us. The freezing of water is known to be its crystallization, and snow is crystallized vapor. The coarse-grained structure of bar-iron is correctly called its crystalline structure; for the grains are all formed by the process of crystallization; and in steel we perceive the same texture, and may trace it through varieties, till the grains are too fine to be distinguished. Granite and all igneous rocks are made up of

* Course of Lectures on Natural Philosophy and the Mechanical Arts, by Thomas Young, M.D., 2 vols. 4to. London, 1807. Vol. i, p. 628.

† *Précis Elementaire de Physique*, 2 vols. 8vo. Paris, 1824. Vol. i, p. 18.

crystallized material; and any one familiar with granite can pick out its mineral grains and exhibit their crystalline character; and if granite is crystallized in its intimate texture, so are all aggregate rocks made up of granite material. Indeed a general survey of the inorganic world develops the truth that here the power of crystallization rules, like vitality in the organic kingdoms. A crystalline texture may not always be apparent. This is the case internally with ice, or a fragment of quartz crystal, although there is no doubt that in each of these instances, the forces of crystallization were the cause of solidification. This is also true of the finest grained steel, as just observed, and some basaltic rocks. But we find, from the transitions in structure, that the apparent absence is owing to the extreme minuteness of the grains and the compactness of texture.

If then, crystallization and solidification are properly one and the same process, the laws that govern in crystallization are the laws of cohesive attraction. The science of crystals instead of treating only of certain singular polyhedral forms assumed by minerals, is the study of the fundamental agency by which inorganic matter is governed in its aggregations: and in place of occupying a short chapter in our text-books on physics, and there, as would often seem, in the way or out of place, it should be made to stand prominently forth as embodying and exemplifying some of the widest elemental truths of nature.

Let us then look at the facts, in order to arrive at these laws. Some of the deductions are by no means new. We commence with the simplest principles, in order to present a general view of the subject; and a few familiar facts in crystallography are illustrated with figures, as the subject may interest some who are not acquainted with them.

1. It is, in the first place, an established fact that the different kinds of inorganic matter have each a distinct mode of crystallization. Every species has certain fixed, determinate, angles, which characterize the structure, both of the crystal and the crystalline grains in a compact mass. Galena crystallizes with a cubical structure; and even in a granular mass, this structure may with care be detected by the rectangular cleavages. So in granular limestone, or common white marble, the oblique angles of the grains are precisely those of the perfect crystals of calc spar. As this is a general truth, *these fixed angles, for each species of matter, in some way characterize molecular or cohesive attraction.*

Again: crystals have plane surfaces, and are prisms or allied forms. Now if the attraction acted alike in every direction it would make only spheres; to produce polygonal forms there must, therefore, be specific directions in which the attraction acts more strongly than in others. For a cube or prism, there must be at least three such directions, corresponding with axes in the

form; and if the prism has oblique angles instead of being rectangular, these lines of strongest attraction must have a corresponding obliquity. Hence *the angles referred to, as characterizing cohesive attraction, are angles between certain imaginary lines, or axes, in whose direction the attraction is strongest.*

Again: the crystalline forms in nature are well known to have fundamentally fixed relative dimensions, indicated by the modifications they undergo (producing secondary forms) though not necessarily apparent in the actual proportions of the crystal. Thus a cube, which is equal in its dimensions, shows it in all its modifications; and in a prism, the inequality in the dimensions is as exactly and precisely indicated by its modifications.* The relative dimensions belonging to the fundamental form of a substance, are often therefore easily calculated; and the whole science of crystals is thus based on rigorous mathematical laws.

From these facts we may conclude therefore with respect to solids, that *Cohesive Attraction is characterized by fixed angles, as regards the direction of its action, and by specific relations of force in certain axial directions; and it differs in these particulars for different substances.*†

These facts are the only hints which nature gives us respecting the axial dimensions of molecules. We proceed on the only possible grounds for any conclusion on this point, when we infer that *molecules have corresponding relative dimensions with the crystalline forms, and the same specific angles between the funda-*

* A square prism and a cube as presented in nature, may have actually the same dimensions, owing to the distortion of the one or the other. But the fundamental nature of their forms, may, notwithstanding, be obvious to the eye. In the cube (having equal faces and axes) *all* the edges will have similar secondary planes (that is, these planes will be identical in their inclinations to the faces of the cube); in the prism, the secondary planes of the lateral edges will differ in their inclinations from those of the terminal. In the cube, there may be a plane on any edge equally inclined to the faces of the cube. In the prism, the plane on a terminal edge will always be unequally inclined to the including faces; such a plane removes a part of the two including faces, and these parts will in all cases have a definite relation to the height and breadth of the prism. These explanations are sufficient to render the general principle stated, intelligible to those unacquainted with the structure of crystals. Treatises on crystals should be studied for a full exposition of this subject.

† Apparent exceptions to this principle are supposed to exist in the case of glass, tabasheer and some other substances that do not polarize light. They are, however, not necessarily exceptions. For in these substances the molecules are either equiaxial or inequiaxial;—if *inequiaxial*, the solids prove that such molecules, with weak polar forces, may be so irregularly aggregated as to show no polarization; and if their form is *equiaxial*, no rings of polarization are to be expected.

We have no facts to determine the form of the molecules in glass. As glass, (common as well as volcanic,) when slowly cooled, produces a different material, with a different temperature of fusion, it must be a dimorphous or isomeric material, capable of taking two distinct forms, of which glass is one. We cannot, therefore, infer that the molecules of glass are inequiaxial from the forms of the crystallized silicates of an alkali. The rapid cooling, necessary to form glass, is the most unfavorable for an axial arrangement of the particles, even if the polar forces were strong.

mental axial lines or axes of attraction. Thus the molecule of a cube must have equal axes, like the cube itself; that of a prism, like axes with the prism in relative dimensions; and if oblique, the axes should have the same degree of obliquity. This statement with regard to molecules is *potentially* true; and in this sense, the only one in which we now speak of molecules at all, it is no hypothesis.

The actual *forms* of molecules constitute another consideration, and one for which we have less precise data. The molecule of a cube may be either a sphere or a cube, as either form would produce a cube by the same mode of aggregation; and that of a prism may be either a similar prism or a spheroid of like dimensions. This is illustrated in the annexed figures 1, 2, 3.

Fig. 1.



Fig. 2.



Fig. 3.



We cannot therefore determine absolutely the *form* of the molecule from the form of the crystal. But from the greater simplicity of the hypothesis that molecules are spheres and spheroids, its sufficiency to meet every case in nature, its necessity to explain optical phenomena, and other considerations we have presented elsewhere, we adopt in this place the view of their spheroidal forms.

By having some idea of a molecule in the mind, we may more easily conceive of the principles deduced with regard to cohesive or molecular attraction.

Our first *inference*, expressed with reference to the molecule will therefore be the following:—

I. *Molecules in solids have fixed relative dimensions for each kind of matter, and certain axial lines of cohesive attraction which are fixed in direction:—*and we add, as a necessary truth, *whose force is inversely related to their length.*

Viewing the molecules as spheres and spheroids, the three axes are the three conjugate axes or conjugate diameters of these forms.* The attraction is not supposed to be confined to the

* If the conclusion be correct that the molecule of the *element* gold is a simple sphere because of its cubical crystals; and that of sulphur an *ellipsoid*, from the unequal axes of its crystals;—it is as good also with regard to *compounds*. Hence the molecule of pyrites (a compound of sulphur and iron), whose crystal is a cube must be a sphere; and that of alum, a spheroid, &c. It matters not whether we can conceive or not of two molecules of sulphur and one of iron, different in size and shape, uniting so as to make a simple sphere. The conclusion is one not dependent for its truth on our conceptions. The finite mind is an *interpreter* of nature and may not presume to the rank of dictator. Its conceptions will be as inane with regard to any kind of combination or mode of aggregation in the above case, which could produce out of such means a symmetrical cube with its faces similar in lustre and every other physical character.

axes, as these are only imaginary lines of concentration of force; the other parts of the molecule must necessarily have attracting force though to a less amount than along the axial lines.*

The fact that crystals are formed by the superposition of molecules by axial attraction, is a matter of observation. In an evaporating brine we may see the minute cube of salt enlarging without change of form, a fact which implies that ranges of particles are added regularly to each side. In a drop of sea water under the microscope, we may watch the growing crystal of gypsum, and see its rhombic and arrow-head forms as perfect in the smallest visible point, as afterwards when more enlarged; proving again that the particles are added in fixed lines, since in no other way could there be this constancy of angle. It is proved again by finding many instances in calc spar, quartz and other minerals, of crystals with internal layers of another mineral which were deposited on the faces of the crystal during an intermission in their progress; showing the form of the crystal in its earlier stages. Hence we may not doubt the reality of the axial lines of cohesive attraction.

Brewster, in the course of his splendid researches on the optical phenomena of crystals, has shown that in some instances the particles are in a state of tension, as by compression. In a recent article on the topaz,† he describes the occurrence, in certain crystals, of extremely minute cavities, which indicate by means of polarized light, that the parts adjoining have been acted upon by a compressing force. Long since he observed respecting the diamond that its crystals,—which are peculiar in having *convex faces*,—exhibit, as he states, “an imperfect, doubly-refracting structure, as if aggregated by irregular forces, and compressed or

* The several axial conditions illustrated in crystals include all the possible variations of the three diameters of spheroids, as is mentioned by the author in an article in this Journal, vol. xxx, 1836, p. 282, and Mineralogy, 2nd edition, p. 79. They are as follows, (using the term *axes* for the diameters having rectangular intersections; and *diameters*, for the diameters having oblique intersections.)

- I. *Sphere*.—Three conjugate axes; equal, (1.) *Cube*.
- II. *Ellipsoid of revolution*.
 - A. Three conjugate axes, the two lateral equal, (2.) *Right square prism*.
 - B. Three equal conjugate diameters, [with equal oblique angles of intersection,] (3.) *Rhombohedron*.
- III. *Ellipsoid, not of revolution*.
 - A. Three conjugate axes, unequal, (4.) *Right rectangular prism*.
 - B. A vertical axis, and two equal conjugate diameters, (5.) *Right rhombic prism*.
 - C. A vertical axis, and two unequal conjugate diameters, (6.) *Right rhomboidal prism*.
 - D. Three conjugate diameters, two equal, (7.) *Oblique rhombic prism*.
 - E. Three conjugate diameters, unequal, (8.) *Oblique rhomboidal prism*.

† L. E. and D. Phil. Mag., August, 1847, xxxi, 101.

kneaded together like a soft gum or jelly." He concludes from the facts, that the topaz must have been in a soft and plastic state while it yielded to the compressing force which emanated from the cavities, and farther, infers (as in 1805 from his experiments on depolarization) "the existence of a new species of crystallization, which is the effect of time alone, and which is produced by the slow action of corpuscular forces."

If the facts prove a comparatively soft state of the topaz when first formed, as they appear to do, they indicate that the crystal while afterwards hardening, would undergo contraction, in which case such minute cavities or any foreign particle would become apparent centres of a compressing force. The regular form of the topaz crystal, presenting a perfect correspondence in every respect with other crystals, can be explained only on the supposition of axial attraction; and while the necessity of time and corpuscular forces must be admitted, we fail to see evidence of a new species of crystallization. In the diamond, the same principle may have operated. If the crystal when first formed is still imperfectly hardened, contraction would continue for a time in progress; and the contraction in this case acting with some reference to radii from the centre, and affecting most the prominent edges and angles, might give the convex form presented by the faces of the crystals, and the peculiar structure within.

The fact mentioned at the meeting of the British Association in June last, by Mr. H. F. Talbot, that a fused globule of nitrate of potash polarized light, like a regular crystal, only shows that some species may retain the axial forces and arrangement in the fluid state. It is known that certain fluids have the power of polarization. These facts extend instead of limiting our proposition, proving that the molecules of some substances, even in the liquid state, may have the inequiaxal forms, generally detected only in solids.*

* Sir David Brewster, after mentioning his grand discoveries with regard to producing the polarizing structure in glass and other substances by tension, suggests that the polarizing structure of crystals arises from the mutual pressure of the elastic particles during crystallization. He concludes that the axes of crystallization are three in number and at right angles to each other, and observes, "that when any two molecules are brought together by the forces or polarities which produce a crystalline arrangement and strongly adhere, they will mutually compress one another, and each will have an axis of double refraction in the direction of the line joining their centres, in the same manner as if they had been compressed by an external force."

The facts are explained, as we believe, more simply and more in accordance with the laws of crystals, by attributing the character of ordinary polarization in crystals to the form of the molecule independent of pressure. The molecule in inequiaxal crystals must be inequiaxal, and this is a sufficient reason, without adding pressure as an additional cause. Pressure at the poles, would only flatten the poles, and this would make an irregular solid of the ellipsoid, inconsistent with the

After these observations, I continue with the statement of facts and the inferences they sustain.

2. In crystals which have unequal axes, the physical qualities of the crystal (such as color, hardness, lustre, &c.) are different in unlike directions; and they are uniformly alike in the direction of equal axes. This symmetrical character indicates that—

II. *In the aggregation of molecules by attraction, only equal or homologous axes unite.*

3. The electrical polarity of many crystals; the occasional dissimilarity of form in the opposite extremities of the same prism; the facts with regard to compound crystals, as well as direct experiments with magnets on the process of crystallization, show that—

III. *The axes of cohesive attraction in molecules have opposite polarity at opposite extremities;—that is, the opposite poles are positive and negative, or north and south, as these terms are ordinarily used.**

4. Many geniculated crystals, are geniculated alike at equal distances from the middle of the prism, (or, are like a column bent alike at two places equidistant from the middle.) They have be-

character of the polarization in crystals. The effect of this flattening of the surface of the molecule by pressure is probably seen in the curious crystals of analcime,^a whose structure has been developed by this distinguished philosopher. In the case of glass and other substances, that receive the power of polarization by pressure, it would seem from the facts just stated, that it depends upon a change by compression of the spherical molecule to a spheroidal or compressed shape; the shape is a result of pressure; but as in crystals, the polarization may be dependent on the shape.

The polarization of molecules will depend not only on their form, but also on their nature, whether uniform in character throughout, or differing in density from the centre to the circumference and with a definite inverse relation to the lengths of unequal axes. As the latter supposition is altogether the most probable, considering that molecules are centres of attraction, the form of the molecule and the form deduced from polarization should not be the same until this law of relation is understood and duly appreciated.

* By polarity we imply simply that relation between the diametrically opposite parts, A and B, of a molecule, by which the part A of one molecule unites to another molecule by the part B, and repels the part A. This property appears to be one of the fundamental qualities of matter or force, as no exhibition of force in nature is divested of it. In solidification this polarity is exerted most strongly along fixed axes.

^a Crystals of the tesseral system to which analcime belongs, do not polarize light; but in specimens of this mineral, a peculiar system of rings has been detected by Brewster: they suggest at once, that like certain cooled cubes of glass, the structure has arisen from a change of form in the molecules dependent on tension.

come thus geniculated simultaneously at both extremities, while they were enlarging, evincing that—

IV. *The polarity of molecules may be reversed by extrinsic influence.**

5. Twin crystals have one half of the crystal in a reverse position from the other.† This may be imitated by cutting a crystal in halves, and after a semirevolution of one half, applying the parts again together; an oblique crystal will thus have a reëntering angle, as in fig. 5. If in fig. 5, A be the position of the nucleal molecule for one half, B must be that for the other. The mode of aggregation for a simple crystal is that shown in fig. 4. The attraction between the two molecules brought them together in either case. But in one the position of the molecules when about uniting was favorable for the direct union in fig. 4; and in the other, the two were in opposite positions, yet so close in proximity that union took place by the adjacent poles without allowing of the change of position necessary for direct union. In the former, the same poles of the vertical axes, are in the same direction; and in the latter, they are in opposite directions. There could not be such an inversion of the molecules, if the axes were a *result* of the act of union. Hence,—

V. *The axes and polarity of cohesive attraction in solidification exist before the union of the molecules, instead of being a consequence of that union.*

6. The forms of inequiaxal crystals vary somewhat with a change of temperature; and at certain temperatures, specific in each case, some substances undergo abruptly a total change of form, both as to the direction and relative lengths of the axes. Hence,—

VI. *The axial lines of cohesive attraction, are not indefinitely fixed in position, but are some way modified in direction and force by temperature.*

Thus far we have considered the general polar condition of cohesive attraction in solidification, its liability to a reversion of the

Fig. 4.

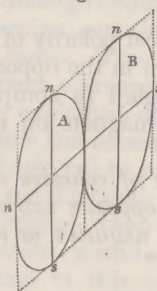
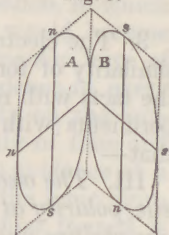


Fig. 5.

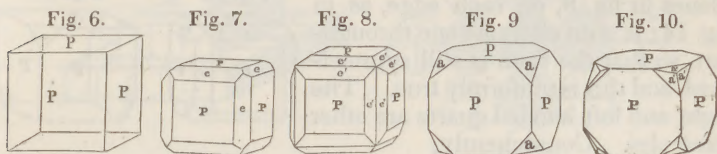


* See an article by the author, in the American Journal of Science, for 1836, vol. xxx, p. 275, and particularly p. 292; also Mineralogy, the chapter on Crystallogeny.

† We consider here but a single kind of twin crystals, in the briefest manner possible, as the facts are sufficient for our deductions. See farther, Amer. Jour. of Science, and Mineralogy, as just referred to.

poles like ordinary magnetic polarity, and its varying in direction with the changes of temperature. There are evidences of other modifications in the condition of the attracting force, which we now consider.

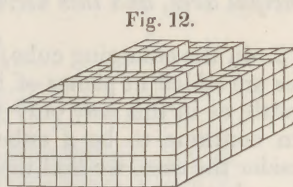
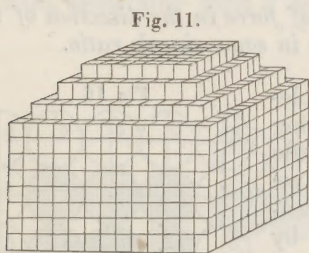
7. The same species of matter often presents a variety of forms in its crystals, built up on a fundamental type. For example, when the type is a cube (fig. 6), the species may occur as cubes; or as cubes with the edges truncated (fig. 7); or with the edges beveled (fig. 8); or with the angles replaced (figs. 9, 10), and so



on. If then a certain state of the attraction in a molecule will produce the primary cube, some variation from this state is necessary to produce another form, and a different variation for every different secondary plane. Consequently,—

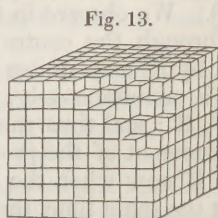
VII. *Attraction of cohesion in molecules of a given kind, is not an unchangeable force, but admits of variations of condition.*

8. The secondary planes of crystals, as related to the axes of the fundamental form, have fixed simple ratios. The plane trun-



cating the edge (fig. 7) referred to the axes, has the simple ratio of 1:1 (fig. 11). Other planes (as in fig. 8) may have the ratios 1:2 (fig. 12), 1:3, 1:4, 2:3, and other simple ratios. Planes on the angles (figs. 9, 10) referred to the three axes, may have the ratios (indicating their positions) 1:1:1 (fig. 13), 1:2:2, 1:3:3, 1:2:4, 2:3:6, 3:5:15, and so on. Hence,—

VIII. *The variations which the attraction of cohesion undergoes, take place according to some simple ratio.*



9. Similar parts of crystals, with a single class of exceptions, are similarly modified. Now as the similar parts are those similarly situated as regards like axes, it follows that—

IX. *The homologous parts of molecules similarly and simultaneously undergo this variation as regards the attraction.*

10. In the excepted cases just alluded to, only half the similar parts are modified alike. In the cube of boracite, only half the angles have similar secondary planes (fig. 15); in pyrites it is usual to find only one of the two beveling planes in fig. 8, on each edge, as in fig. 14; it is an alternate one throughout, so that the form is still symmetrical, and this is uniformly true. The right and left handed quartz are other examples. Consequently,

X. *In some cases, the parts of a molecule on opposite sides of a pole undergo a different amount of variation of attraction; this takes place symmetrically with regard to all the poles.*

11. In the formation of a cube with truncated edges, the cube is not finished out on the edges. There is therefore a diminution of the force of attraction in the line of the primary axes, since these axes fail of completing the cube. Hence,—

XI. *If the state of the attraction which produces a primary cube or prism is considered its normal state, when secondary planes are produced there is a decrease of force in the direction of the principal axes, and this decrease is in some simple ratio.*

12. In the enlarging cube, the molecules are added in planes of increasing breadth, as in this way only would the form continue to be a cube. If we consider the case, we find that the central molecule attracts a molecule by each of its poles, and also simultaneously the added molecules act by their lateral axes to complete the plane (fig. 1). We observe in the sectional view (through the centre) in fig. 16, when A by its axes unites with four B's, the B's, simultaneously, while in the act of union, unite with B', B', B', B'; and thus the square form is retained. This is a simple statement of the process.

If now when the B's are uniting, their lateral axes do not act at the same time, then the forming cube will have the edges trun-

Fig. 14.

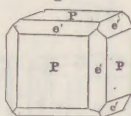


Fig. 15.

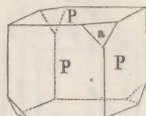
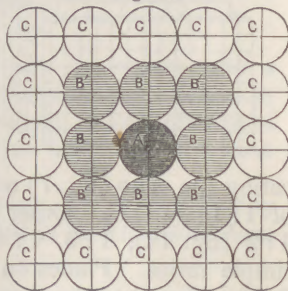


Fig. 16.



cated as in fig. 11. To understand this we must study the steps in the process. Fig. 17 represents the same secondary planes as in fig. 11, without the primary faces. It is obvious that in the enlargement of such a secondary, when the summit molecule is annexed, its lateral axes do not act as they do when a cube is formed:

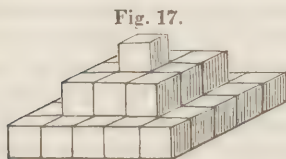


Fig. 17.

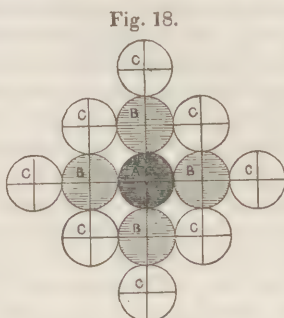


Fig. 18.

when another molecule is added beyond, then they act laterally. This may perhaps be more clearly seen in the transverse section in fig. 18. When A attracts B, B does not act laterally as in fig. 16; it does not so act until B attracts C, when a C is added either side of B. So C acts laterally when a D is added to C, and not before.

Again in fig. 19, we have a section of another figure, (the same secondary as in fig. 12,) showing the arrangement of molecules in a solid, presenting such a section. Examining it, we perceive

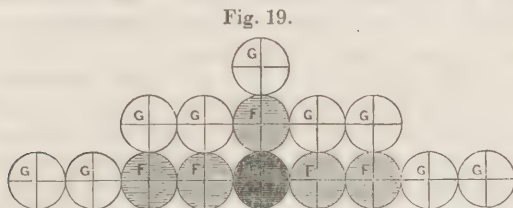


Fig. 19.

that when G is added to the extremity of the central axis, two molecules, G, G, are added on either side of F, and none laterally to G. This figure represents the formation of the secondary plane having the ratio 1 : 2, as is evident from inspection, and fig. 17 or 18, another with the ratio 1 : 1.

If the period of time occupied by the union of a molecule be represented by p , then when the lateral axes act only after the period of time p , and then add a single row of molecules, the secondary plane is the truncating plane 1 : 1; for the plane having the ratio 1 : 2, in which two are added laterally to one terminally, or what is equivalent, one laterally for every half a one terminally, the time would be $\frac{1}{2}p$; for the plane 1 : 3, the time would be $\frac{1}{3}p$.

To understand the origin of planes on an angle, we must again consider the actual circumstances. Fig. 20 (the same secondary as in fig. 13) will aid the mind in conceiving of it. Here, when the summit particle unites itself, it adds nothing laterally, as was the case also in fig. 17; when another unites beyond,

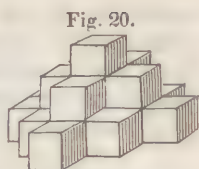


Fig. 20.

then four particles are united, one by each lateral pole; but these four add nothing, until still another particle is added to the summit. In this case there is an interval of time p , between the action of the terminal and lateral axes, and another interval p' , between the adding of the four molecules and the action by *their* lateral axes. And this is the difference between the plane truncating an angle (figs. 9 and 13), and another truncating an edge of a cube, (figs. 7 and 11.) This plane truncating an angle has the ratio 1 : 1 : 1. For a plane 1 : 2 : 2, the times will be each $\frac{1}{2}p$, and for any plane 1 : m : n , the times will be $\frac{1}{m}p$ and $\frac{1}{n}p'$.

It appears that the lateral axes act less speedily therefore for the truncating plane of an angle, than for that of an edge; the centre of the former in a cube is $54^{\circ} 44'$ from the centre of a face of the cube, and the centre of the latter from the same is 45° .

We have before observed, that the production of secondary forms depends on the fact, that the force of attraction in the axes of the molecules when secondaries are produced, is less than that which is exerted when the primary prism or cube is formed. But we cannot suppose the whole force of attraction in a molecule to be different in different circumstances. No facts nor reasoning would sustain this conclusion. We may admit that the attraction may be more concentrated in the primary axes, in some cases than in others. It is well known that the polar condition in bodies does not imply an addition of force, but simply an axial action or concentration of the force. This concentration or excited action may be induced by the condition of neighboring bodies or influences: and different bodies should differ widely in their susceptibility to it, as is evidently the fact. Now if the attraction is less concentrated in the primary axes, when a secondary plane forms, the *interval of time* above alluded to as characterizing the formation of different secondaries, will be longer or shorter according to the state of concentration in the primary axes. The more or less diffused state of the attraction is connected with the kind of secondary produced.

But when we observe in a complex crystal, the evenness of the faces, the neat regularity of the edges, and the perfection throughout, even when many secondary planes are combined, it appears clear that such forms could not result from simply a generally diffused state of the attraction, any more than a primary could be so produced. In each case there must be as many distinct axes

as there are planes. When therefore the principal axes lose their concentration, this loss consists in a distribution of the force into subordinate axes intermediate between the primary axes. For a truncation of the edges of a cube, the intermediate axes would have their poles just at the middle point between every two poles of the primary axes; for a truncation of the angles, the poles would be at the middle point between every three poles. We have remarked upon the symmetrical arrangement of secondary planes in general, and this would follow from the necessary symmetrical arrangement of such axes. Moreover the length of time p , will be greater the farther the secondary pole is situated from the primary poles. And this is true in fact. The pole for the octahedron is the most distant, being at the central point between three primary poles.* The number of combined secondary forms may still seem mysterious. But a crystal, in its capacity as a unit, would necessarily have a corresponding character in its different parts to the molecules of which it consists, and consequently the attraction exerted by the molecules in these different parts would correspond, occasioning thus the secondary planes. Moreover the relative extent of the several different kinds of planes, will depend primarily on the relative force of action in the different sets of axes.

These considerations lead us to conclude, that—

XII. *The diminution of attracting force in the primary axes, on which the formation of a secondary depends, consists in the partial action of this force along intermediate axes, symmetrically situated with reference to the primary axes; and the greater or less amount of diminution, determines the kind of distribution.*†

13. The same crystalline forms, may have different cleavage in the case of different species of matter. Thus, cubes of galena have a cubical cleavage, while cubes of fluor spar have an octahedral cleavage or yield octahedrons when cleaved. In ordinary crystallographic language, the cube is therefore said to be the primary of galena, and the regular octahedron is the primary of fluor spar. These different circumstances would result, provided that in one case (for galena) the three primary axes of the molecule were dominant, and in the other the eight intermediate or octahedral axes. The arrangement of the molecules in each case would depend on the dominant axes, and so also would the direction of the cleavage. Hence,—

* Here is evidently basis for mathematical calculations of some interest.

† In the case of substances that very seldom crystallize or never, we have evidence that the polar forces are very weak. The attractive force may be so diffused as to approximate to the ordinary state in liquids.

XIII. The direction of cleavage may indicate in any species of matter which set of axes is dominant, the primary, or a secondary set.

In the preceding paragraphs, after ascertaining the general polar action of cohesive attraction, we have pointed out the modifications of condition this attraction undergoes, the simple ratios presented by these modifications, and their dependence on the formation of intermediate axes. Cohesive attraction instead of being a constant force, as might be inferred from the ordinary definitions, appears therefore to be complex in its actions, yet simple in the general laws by which this complexity is produced.

14. The absence or presence of secondary planes, and their character, are known in some instances to depend on external circumstances. Electric currents, the nature of the supporting rock, or the condition of the solvent are determining causes. A floating crystal has been seen to form secondary planes on becoming attached. Crystallizing in a thick pasty mass as Beudant has observed, will generally afford the simpler forms. The most complex are usually the purest crystals, such as have been produced in the most quiet circumstances. Implanted crystals are sometimes rendered more complex during the last stages of their increase than they were before. These facts show some of the ways by which modifications in the condition of the attraction in the primary axes are produced. The presence of foreign material, sometimes, or whatever may sustain an excited state of polarity in the primary axes, will occasion the formation of simple forms. But if there is nothing to sustain or excite this concentration, or the action is quiet, or if bodies around induce it, owing to their own condition, the attraction becomes more diffused, and secondary axes multiply.* All the crystals of a locality or region have usually the same form. The constancy of certain forms in some species is evidence of the peculiar susceptibilities of the molecules of those substances. Thus the calc spar in the limestone of Lockport has the dog-tooth shape, the scalene dode-

* The theory above offered with regard to the origin of secondary planes, is near that presented in 1839 to the Royal Society, by Prof. Necker. How far they are identical, I cannot decide with certainty from the brief notice of his paper, which I have seen in the *Philosophical Magazine*, vol. xiv. p. 216. M. Necker supposes that there is a tendency in crystals to take the spheroidal forms of their molecules; that when the secondary axes are destroyed by different causes, simple crystals are produced. According to the view here presented, there is no tendency of this kind recognized; the concentration of the primary axes producing simple forms is the ordinary condition of the molecules of some substances in solidification; and by this concentration, however produced, the secondary axes lose their force. The view I had gathered from the abstract of M. Necker's memoir, is given in a note to page 100 in the author's *Mineralogy*, 2nd edit., New Haven, 1844.

cahedron; that of Boonville, New York, occurs in short six-sided prisms. That of the Rossie lead region in complex combinations of different secondary planes with the primary.

XIV. These facts indicate, that *the variations of attraction, producing secondary forms, depend often on surrounding bodies favoring the concentration or diffusion of the attracting force; and the causes often act simultaneously in nature over wide areas.*

15. It is also a usual truth, that crystals are sometimes very much lengthened beyond their normal proportions, and in other cases, very much shortened. When attached, they are lengthened or shortened in the direction of the axis of attachment; and if obliquely attached, they are distorted in this direction. These facts, which are of common observation, show that—

XV. In an enlarging crystal, *one axis (or two) may have the action of attraction more accelerated or retarded than another by extrinsic influence, and this acceleration or retardation affects equally all crystals forming together under common circumstances.*

16. The peculiarities of cleavage give us information on another point respecting cohesive attraction. The facility of cleavage in prisms differs in the direction of unlike axes. Topaz cleaves easily parallel to the base of the prism, and not at all in other directions. This difference does not depend upon the relative strength of attraction in the unequal axes; for it is often the reverse of this. Again, while some of the hardest substances have perfect cleavage, other soft species have none.

If then this quality has no relation to the strength of the attraction which unites molecule to molecule, it must depend on some peculiarity in the manner in which this force acts. This force may act in two ways:—either *continuously*, or *intermittently*; and the latter mode only, could produce the result in view. The action of force in nature appears to be generally intermittent. Alternate action and comparative inaction, with corresponding results, are every where exemplified in organic growth; and it is therefore no anomaly that it should be exemplified in the inorganic kingdom.*

* The successive layers in wood, the periodical reproduction of leaves or flowers, and of young in animals, and the seriate arrangement of parts in many plants and animals all illustrate intermittent growth. In some zoophytes the buds form in successive series of two, four or six, or some other fixed number; in other cases opposite sides alternate in budding, or when there are several rows, the rows bud in succession; and these are examples of intermittent action.

The spiral arrangement of leaves in vegetation, as I have elsewhere observed, (Zooph., p. 89.) is another illustration of intermittent growth; for here the different sides of the growing plant (*five*, in many plants, and *six* in many others) bud

We infer therefore that when cleavage is produced, the union of layers of molecules takes place by an intermitted action; that is, with regular successive variations or pulses in the intensity of the force of attraction. This intermitted action when reduced to simply the adding of single layers in succession, becomes continuous. On these principles there might be every variety of this quality in nature, and there should be no necessary connection between cleavage and strength of attraction. We therefore infer that—

XVI. *The action of cohesive attraction is often intermittent, producing seriate results, (as exemplified in the cleavage of crystals,) and the specific rate of intermittent action is different for unequal axes.**

17. Cohesive attraction may be partly controlled in its results by gravity, and by rate of solidification or of chemical combination. It is evident that in the cooling of a liquid mass, when the temperature of solidification is reached, there will be numberless points throughout the mass where the molecules will commence the process of crystallization; and acting together, they would produce an aggregation of small crowded crystals or grains, with no external regular forms, in other words, the *granular* structure. In cases of a crystallizing solution, the same result may happen, if the process be rapid.

Again, a thin solution spread over a large surface, would produce crowded minute points; and if the solution be gradually supplied, as the crystallization goes on, it is obvious that the minute points crowded together might elongate into crowded prisms,

successively, for the simple reason, of universal application, that reproduction produces temporary exhaustion, or, that force is exerted intermittedly.

The *pulsation* of molecular force is also an example of intermitted action, and must lie at the basis of the universal principle on this subject to which we have alluded. The reality of this pulsation, insisted upon by Mr. J. D. Whelpley in 1845 before this Association,^a and also by Faraday,^b we cannot doubt. The undulatory theory of light must be received as fully demonstrated: and if it is an ether that pulsates, it is molecular force which makes it pulsate, and this implies pulsating action in molecular force itself.

The attraction of cohesion is shown by cleavage to be intermitted in *intensity*; we do not learn from it that there is any actual intermission of time in the exertion of the force, or a variation in rate of pulsation.

* Many crystals have their surfaces covered with parallel striations which consist of alternations of two or more sets of planes. Thus cubes of pyrites very generally have their faces marked with striæ which are oscillations between a plane replacing the edge, and either the face of the primary cube, or another plane of the same secondary. Some octahedrons of fluor spar have faces which consist of minute cubes. These facts, and they are common and well known, show frequent intermitted mode of action in the different axes of molecules, (or a seeming strife between different sets,) producing what has been called an "oscillatory combination" of planes.

^a Rep. Proc. for 1845, and also this Jour., xlviii, 352, and ii Ser., ii, 401.

^b Phil. Mag., May, 1846, and this Jour., ii Ser., ii, 401.

and produce a fibrous structure. Such a structure is common in narrow seams in rocks, proceeding either from this cause, or perhaps in part from the electric influence of the adjoining walls of the seams.

The concentric structure is another result depending on the rate of solidification connected often with the rate of chemical combination. In the first place the nucleus is always a cluster of molecules, instead of a single one as for a simple crystal. The structure sometimes commences around some foreign body as a centre, though the aggregation is often without any proper nucleus, except that of the cluster of molecules that first solidified. The second principle, on which the concentric structure depends, is the tendency of a body to communicate its own condition to other bodies within its influence. This law—the law of equilibrium, and contact, or catalysis in chemistry—is one of the universal laws of existence. According to it, either a collection of molecules entering the solid state, or any foreign body already solid will tend to bring adjacent bodies into the same or an intermediate condition. If susceptible to this influence, the particles adjoining become assimilated, and unite to the nucleus; these again act upon others adjoining, and thus a spherical form is produced, as a result of successive development. In glass that has cooled with extreme slowness, there are often spherical aggregations of crystals. Here, in some single point, the mineral of the aggregation first began to form; and once begun, the process was continued, according to this law of influence, around the point as a centre, and the aggregations are therefore spherical. In cooling basalt or granite, large spherical concretions are often formed. The process of solidifying is in these cases continued through a very long period of time; and from the relation often perceived between the thickness of a bed of basalt and the size of the concretions, this size is evidently greater the slower the cooling. In this prolonged cooling, after a while, here and there a spot reaches the solidifying condition, and the process commences. The particles adjoining, as explained, become solid about the spot; thence the process extends itself equally in every direction; and spheres are the result. The slower the cooling, the longer the time occupied in passing through a single degree of temperature; and consequently, when the cooling is most gradual, the centres would subordinate to themselves a large amount of material, and produce larger concretions.

In other cases, a solution is infiltrating through a clay or sand:—something (it may be a harder point or spot, or some organic object) determines the commencement of solidification at certain points in the clay, and from this, the process continues by simple propagation, as just described. The stratification of the clay, or texture arising from gravity, favoring infiltration laterally more

than vertically, will often cause such concretions to be flat; and when they become very numerous, a bed of concretions is changed to a solid bed of compact rock.

In still other cases, a molecular change of the same general character and on the same principle, goes on after consolidation has taken place.

The structure of such concretions must depend on the material constituting them. The mode of formation, and the general property that attraction has a definite relation to distance from a centre, will give them a similarity of character, in corresponding parts. The constituent crystalline grains, when any are apparent, will have necessarily a corresponding position with reference to the centre. A foliated mineral which in one part had the foliation concentric in the spherical mass, would have for the reason stated, the foliation concentric throughout; and a fibrous mineral, with the fibres radiating from the centre, would retain this structure regularly.*

These considerations sustain the conclusion, that—

XVII. Cohesive attraction produces spherical concretions, about a cluster of molecules as a nucleus, through the tendency of molecular action or condition to propagate itself; and concentric aggregations begun, act under the general influence of the radial action of attraction in a mass, which action, other things the same, is equal at equal distances from a centre.

We might consider other effects of cohesive attraction, and extend our remarks to liquids and gases. But this paper has already reached an undesired length, although giving but the outlines of a subject that admits of great extension; and the consideration of liquids and gases in the present state of our knowledge would involve us in speculations that we have purposely endeavored to avoid.

We have thus endeavored to follow out the various facts presented by matter as it exists around us. Observation has proved more profitable than closet speculation in animal and vegetable Physiology; and so it will be with regard to the grand organizing force of the so-called inorganic kingdom,—the basis of Mineral Physiology. The fact that the attraction of molecules is liable to modifications of condition, and especially the simple yet fixed relations between these modifications, nothing but a crystal could make known to us. Yet the principle is as wide as the universe in its application; for we live in a universe of molecules, and all the grandeur of physical nature is the result of molecular forces.

* The concentric structure here explained is analogous in many respects to the circular and spherical forms in vegetation. The growing lichen extends itself circularly, owing to progressive assimilation or development. This proves no similarity of nature between the organic forces and cohesive attraction; it only shows that different forces act under a common law.

Through the preceding pages I have intentionally avoided allusions to the actual nature of molecules, as the conclusions are independent of any views on that subject. Even form and size are not essential to the deductions, as what has been designated the lengths of the axes, may be viewed as the inverse ratio of the attracting force in the axial directions. If the existence of an ether be insisted upon as surrounding the molecules, the relations are none the less correct.

The facts however prove that in the action of cohesive attraction there is a limit to penetrability, fixed in different directions for given temperatures; and this limit is essentially a limit of form and size; and as the phenomena of light are dependent on molecular forces, we cannot deny to molecules color and other qualities of sensible objects.

The ether appealed to in order to explain the phenomena of light,—admitted to have none of the qualities of matter and yet often spoken of as a real existence,—is a kind of machinery, summoned for the sake of an explanation; and since we may now believe that instead of such an ether capable of pulsations, *pulsating molecular force* itself will afford as perfect an explanation of the phenomena of light, the necessity of the ether even as an hypothesis is done away with.* There is therefore no reason from this source for doubting the conclusion that the forms of molecules and their relative dimensions, as ascertained from crystals, are their real forms and relative dimensions.

The phenomena of heat as explained by received theories, seem to present a similar objection to the view we here take, since an ether or a mysterious imponderable agent is supposed to intervene between the molecules in the expansion of solids, and by its arrangement to cause the change of axial directions. But the assumption of this *tertium quid* gives us no aid in understanding the change of axial direction, and the general law with regard to attraction, on which we must fall back in either case, will be much simpler without it. Neither, as my friend Mr. J. D. Whelpley has argued, is this hypothesis necessary in order to explain expansion. Since molecules may undergo all the various modifications of condition and form which have been pointed out, it is not improbable that they should also admit of change of size. Size is known to be directly related to temperature: every degree of temperature in a given substance is connected with a specific size. To effect a change of size in molecules, attraction, the same which has been shown to vary in concentration and other particulars, must also vary in radial force. The variations which have been pointed out are caused by induction, according

* See note, page 379. This principle, like the theory of gravitation when first presented, rose into view to simplify, just when theoretical science was becoming encumbered with rapidly increasing perplexities.

to the general law of mutual influence, or tendency to equilibrium, and no other law is required to explain a change of size. For if there were in existence molecules of the same substance of different sizes (or in other words of different temperatures), there would be between them a tendency to equilibrium of size (or in common language, to a mean temperature); and thus this simple law of mutual influence will explain enlargement or contraction from variations of temperature; and the variations from a mean size, (a mean temperature,) arrived at when two *different* substances mutually act on one another, will be specific heat. The change of form and axes in molecules dependent on change of temperature, will be a consequence of change of size, according to some law yet unascertained.

This view, for which we are indebted to Mr. Whelpley, explains expansion without recourse to any intervening ether, or any imponderable agent, excepting the general force of attraction. Admitting these conclusions, it will follow that the forms deduced for molecules are their actual forms. We confidently believe it will soon be shown that this change of size and attendant changes in pulsating force, will sufficiently explain the physical effects of heat.*

A *molecule* according to these views, is spherical or spheroidal in form:—

It exerts attraction in every direction; but this force on opposite parts is so related that one molecule attracts another by one side and repels it by the opposite (polarity):—

In solidification (and sometimes before?) this attraction is axially polar; it admits of various degrees of axial concentration or diffusion, (§ 7 to 12,) of acceleration or retardation of action, (§ 15,) and of different degrees of radial force, which variations take place under the general law of mutual influence, or tendency to an equilibrium:—

This attraction acts by pulsations; in solidification there are also compound pulses (undulations in intensity) consisting of a series of pulsations, and producing intermitted or seriate results (cleavage), which results are in all cases specific; the same pulsations (the optic nerve being sensible to them) produce the phenomena of light; they are also a means of producing chemical effects, especially when the pulsations exceed the rapidity of those for light, (the *chemical* rays being those beyond the violet ray or those which have been shown to be most rapid in vibration.) The α and β states of elements, or their passive and

* The relations of heat and magnetism, are illustrated in a valuable article in this volume, by Prof. W. A. Norton, pp. 1 and 207; and some following pages contain an interesting memoir on heat and light by Prof. Draper.

active states,—the former changing to the latter under the action of light or the chemical rays,—will be different states induced by or through rapidity of pulsation, the rapid pulsation of molecular force (causing or constituting what we call chemical rays) inducing the same rapid action in molecules under their influence. Magnetism may be a condition in which the attractive force is in constant active onward transfer from particle to particle, and galvanism, a condition of similar transfer while an exciting cause is in operation.

In hemihedral prisms like those of tourmaline and topaz, the molecules must have been in this magnetic condition; for they exhibit polarity now when heated. In the *right* and *left handed quartz* and similar cases, where while forming one side of a molecular pole must have been differently affected from the opposite, we may believe that the pulsations were alternate along each axis, *a, b, c*; this would in fact be a spiral action and it would produce a right and left handed crystal, according as the spiral action was to the right or left.

We accord in many particulars here stated, with the general theory of molecules and molecular forces presented lately, with some important shades of difference, by Whelpley and Faraday, and based on that of Boscovitch.

The explanations offered show that very many of the phenomena of physical nature, may be understood on the idea that molecules are simply centres of attraction, the same attraction whose laws have been under consideration. But no property of cohesive attraction explains the *limits* and *proportions* observed in chemical combination. The ultimate nature of the molecule, or of the forces constituting them, (on which we forbear from remark in this place,) is our only appeal for an explanation of these chemical relations. When fully understood, it may appear that cohesive attraction with all its laws, is only a necessary result of this peculiar constitution. We need yet some facts to make it obvious how both classes of phenomena, those of aggregation and chemical combination, may be united in one continued series.

These theoretical suggestions on molecules are annexed to the preceding article, partly in elucidation of some facts before stated, but more especially to exhibit the bearing of the principles on different theories respecting the constitution of matter, and to show that what may seem to be discrepancies are not necessarily so.

There is a strange variance between the chemist and crystallographer. In treatises on chemistry, a theory of molecular forms is often presented as the truth in a chapter on crystals, the falsity of which is taken for granted in all the other parts of the work.

Nature with more consistency, points to a unity of truth. This truth cannot be reached through any one avenue of science. Chemistry teaches us the laws of combination governing molecules, and the attendant operations of molecular forces;—crystallography indicates to us the forms of molecules and the laws which govern in molecular aggregation;—the eye being sensible to the movement of molecular force, optics teaches us the rapidity, character, and physical effects of its pulsations:—and we add by our thermoscopic instruments, another sense, for ascertaining other laws of molecular action. When the mind is fully opened to all these several sources of light, their concentrated beams will enable us to see beyond doubt the minute molecule almost with the distinctness of visibility.



To Prof. Jeffries Wyman
with the author's best regards

